Appendix III: Columbia River Sediment Load

Analysis of Sediment Loading: Motivation

As discussed in Appendix II, deposition and erosion patterns predicted by numerical sediment transport models typically show high sensitivity to boundary sediment inputs. Appendix II analyzed the sediment load delivered to Portland Harbor from the Willamette River. Here we examine loading from the Lower Columbia River, for both sand and fines.

Data Sets

Sediment concentration and load data were collected in the Lower Columbia river (LCR) by the US Geological Survey (USGS), both during the 1960s (to determine the fate of radionuclides released from Handford), and post-1973 by the USGS NWIS program (focused on water quality). For analyses of the Willamette River sediment load, the 1960s Hanford and later NWIS data were collected at the same location (the Morrison Street Bridge) and were similar enough to be combined. But Figure 1 suggests that there are systematic differences between the two LCR data sets: a) Vancouver (1962-1969), and b) Warrendale (1973-2005). It is important, therefore, to determine the reason for the differences between the two data sets, and this necessarily involves determining the load data from the Sandy River, the major lower Columbia River (LCR) tributary between the two locations. The data sets employed in this analysis can be described as follows:

a) Hanford related data 1962-1969: Daily and sometimes more frequent total load data were collected from 1 October 1963 to 31 October 1969, in a study focused specifically on sediment transport processes. Data were collected at several locations including Pasco, Hood River and Vancouver during July 1962 to September 1963; only the Vancouver data are used here. After 1 October 1963 the only data available are from Vancouver, but documents made available during the Hanford Dose Reconstruction Project suggest that additional data were collected, e.g., at Umatilla. The data after 1 October 1963 were reported at the USGS sediment transport web site (http://co.water.usgs.gov/sediment/seddatabase.cfm). The July 1962 to September 1963 data are provided only in Haushild et al. (1966), in the form of graphs. This early part of the data set is extremely valuable, because total load and coarse load (excluding silt and clay) are presented separately, and this is the only source of such data for the 1960s time period. These data were previously digitized at a time resolution of one point every two days (Templeton and Jay, 2013), which is consonant with the graphic form of the data. Additionally, Waananen et al. (1971) provide four data points during the December 1964 flood that define percent clay, silt, and sand. The total number of daily (or semi-daily) data is 2421; there are 229 semi-daily estimates of fine and coarse load, but only 110 sand-load values were >0.

b) Warrendale NWIS data 1973 to 1975 (USGS Station 14128910): NWIS data were collected for short periods at RM-102 and other lower Columbia River (LCR) locations, but the only long-term data set available is from Warrendale, below Bonneville Dam. Data are available irregularly and usually not more than monthly from 1973 to 2005. Most samples also report percent fine material. Early NWIS samples that used the USGS 00530 sampling protocol were disregarded, because they seemed to have anomalous values, likely for reasons described in Gray et al. (2000).[1] Thus, total load determinations were based on 237 measurements of "Total Suspended Solids" (TSS, USGS sampling protocol 80154); 196 determinations of sand load and fines load are available from the 237 total load samples, based on percent fines (USGS sampling protocol 70331).

c) <u>NWIS data – Sandy River near Marmot Dam (USGS Station 14137000) and Below Marmot Dam (USGS Station 14137000)</u>: Data were collected at these locations for a short period in 2005 and 2006, before dam removal in late 2007. They are, therefore, descriptive of the period before 2005, when NWIS data were collected at Warrendale, but do not describe the contemporary situation in the Sandy River. A total of 39 samples are available, all of which have percent fines; sand was absent from 4 samples.

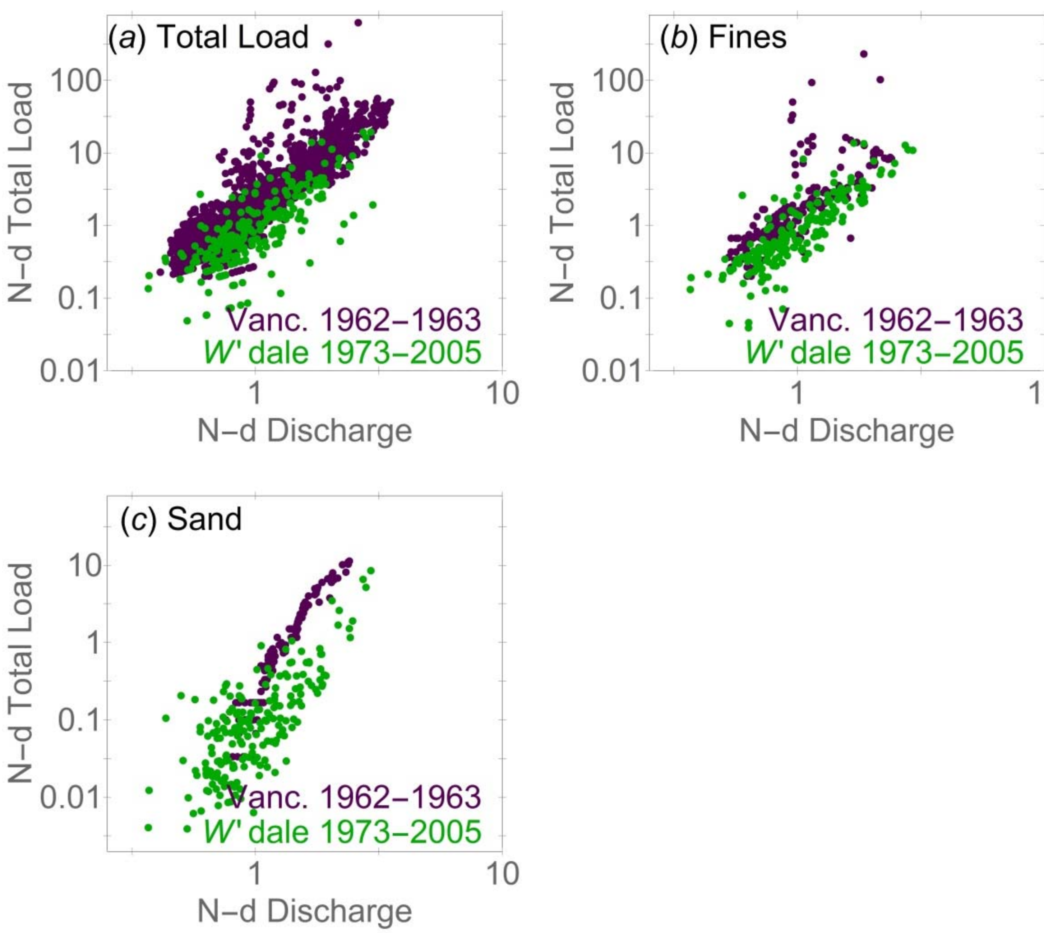

Figure 1: Log-log plots of: non-dimensional total sediment load (a), the fines load (b) and sand load (c) at Vancouver (1962-1969) and Warrendale (1973-2005). Systematic differences are evident, especially in the sand load.

[1] Some differences between the 1960s and the NWIS data sets were also noted for the Willamette River at Portland. These differences were, however, much smaller than those for the two LCR data sets.

Differences between the Warrendale and Vancouver data sets

Table 1 summarizes the differences in the sediment loads at Warrendale (1973-2005) and Vancouver (1962-1969) shown in Figure 1 – the loads measured at Vancouver were larger, especially for sand. Further analysis shows that the Warrendale and Vancouver loads are different in all seasons (not shown). Table 1 also summarizes transport estimates for the Sandy River. Note however, that the Sandy River estimates are based on <40 measurements and should be regards as rough estimates. Figure 1 and Table 1 raise the question of which data set should be used, given that the Vancouver data correspond to the location of the upstream LCR numerical model boundary, but may be outdated. The answer depends on the reason(s) for the differences between the data sets. There are at a number of possibilities:

a) Tributaries: Several tributaries enter the LCR between Warrendale and Vancouver, the largest of which are the Sandy and Washougal Rivers. These (and other ungauged tributaries) have a drainage area of about 942 mi^2, relative to the total LCR drainage >241,000 mi^2 above Vancouver (Orem, 1968). While this is a small percentage difference in terms of area, flow intensities and sediment loads are relatively high for these west-side tributaries, and the name "Sandy River" is appropriate. The Sandy drains volcanic terrain on the south and west sides of Mt Hood. A lahar on Mt Hood in about 1790 provided a very large amount of sediment, and the Sandy River still had, despite its small drainage area and several dams, a considerable sediment load in 2005-2006. The above 2005-2006 Sandy River data (representing an area of 264 mi^2) were analyzed to determine whether they could account for the differences between the two data sets (Table 1). To determine whether the sediment load of Sand River and other tributaries between Bonneville Dam and Vancouver could account for the differences in the LCR load estimates for the 1960s and for the 1973-2005 period, the loads for the Sandy River were multiplied by the ratio of total area to the Sandy River basin area above Marmot Dam (942 mi^2 to 264 mi^2); see Table 1. This is very likely an overestimate of the load provided by these tributaries, because the Bull Run reservoir traps the load from part of the area in question. Even with this generous estimate of the load between Warrendale and Vancouver, differences between the Warrendale and Vancouver data sets remain.

b) Snake River and John Day dams: The four dams on the lower Snake River, completed between 1962 and 1976, are thought to capture 2.3 to 3.1 x 10^6 m^3 (3-4 x 10^6 yd^3) per year of sediment (US Army Engineers, Walla Walla District, 2002). The total amount trapped between dam closure and 2000 was 76.5 to 114.7 x 10^6 m^3 (100-150 x 10^6 yd^3). However, these dams are upstream of McNary Dam, completed in 1954, before any of the LCR sediment transport data discussed here were collected. A considerable fraction of the sediment load not trapped before completion of the Snake River dams did not reach the LCR because it was trapped by McNary Dam. Only clays and part of the silt would have been passed on to the Columbia River below MacNary Dam (US Army Engineers, Walla Walla District, 2002). The amount of material trapped by John Day Dam (completed in 1971) is not known, but "thick" deposits of sediment (estimated 0.25-0.5m) covered 8.7% (12.2 x 10^6 m^2) of the reservoir area behind John Day Dam in 2000, with only a "dusting of fine sediment" elsewhere (Cross and Twichell, 2004). The volume of sediment involved in these thick deposits is perhaps 3 to 6 x 10^6 m^3, most of it being mud. Even if an

c) **Table 1:** Sediment Loads Estimated from Observations LCR Stations between Warrendale and Bonneville Dam[1,2]

Location/Load Type	Minimum	Median	Mean	Maximum
	mtons d^{-1}	mtons d^{-1}	mtons d^{-1}	mtons d^{-1}
<u>Total load</u>				
Warrendale 1973-2005[1]	248	4223	9250	99,000
Sandy River 1973-2005[2]	13	295	572	6220
Warrendale+tributaries[3]	364	6410	11,290	101,000
Vancouver 1962-1963[1]	1015	5110	26,560	3.18×10^6
Vancouver Dec 1964				4.89×10^6
<u>Fines load</u>				
Warrendale	26.2	3380	7840	69,800
Sandy River	4.1	51.9	81.2	570
Warrendale+tributaries	100.4	3750	8130	70,300
Vancouver 1962-1963	1022	5110	15,000	256,000
Vancouver Dec 1964				4.84×10^6
<u>Sand load</u>				
Warrendale	0	436	1590	43,600
Sandy River	0.04	9.1	60.2	1540
Warrendale+tributaries	0.14	578	1780	43,671
Vancouver 1962-1964	0	3920	11,100	57,900
Vancouver Dec 1964				48,900

d) [1] Values for Warrendale and Vancouver are based only on observations. They are not calculated from rating curves.

e) [2] Sandy River loads were estimated from rating curves for all dates when load data were available at Warrendale.

f) [3] The Warrendale+tributaries estimate scales up the Sandy at Marmot flow estimates by a factor of 942/264, under the assumption that all tributaries between Warrendale and Vancouver produce as much sediment as is measured for the Sandy River at Marmot Dam. This assumption likely overestimates the load provided by these tributaries.

equal volume of sediment is contained in the "dusting of fine sediment" in other areas, this trapping is small relative to that in the Snake River Reservoirs, probably of the order of 0.1 to 0.2 x 10^6 m^3 of fine material annually. If it is assumed that perhaps half of the material trapped annually by the Snake River reservoirs represents fines that would have reached the LCR post 1954 but before completion of the Snake River dams, the loss of fine sediment input to the LCR is perhaps 1.1 to 1.6 x 10^6 m^3/yr. It is difficult to know what bulk density to assign to this volume, but it is unlikely that the material trapped represents more than 1.2 to 2 x 10^6 mtons/yr (an mton is a metric ton) of fines. To evaluate the possible role of reservoir trapping, fine sediment transports at Vancouver, Warrendale and Marmot Dam are documented in Table 1, based on the data described above. The differences in fines transport between Vancouver and Warrendale (and between Vancouver and Warrendale plus the Sandy River) may be related to dam construction in the Snake River basin, as discussed below.

Now consider the LCR sand load. There is a deep sand bed at Vancouver, and sand transport there is likely to be transport capacity limited (Templeton and Jay, 2013). Sand transport at Vancouver should decrease, therefore, only due to bed degradation, or due to long-term changes in the flow regime. For any given flow level on a sediment load rating curve, only bed-degradation is relevant. There is some evidence that bed degradation has occurred, likely due to lack of supply and sand mining (Templeton and Jay, 2013; Jay et al., 2011). To evaluate the possible role of reservoir trapping, sand transports at Vancouver, Warrendale and Marmot Dam are documented in Table 1, based on the data described above. The differences in sand transport between Vancouver and Warrendale (and between Vancouver and Warrendale plus the Sandy River) are large and unlikely to be related to dam construction in the Snake River basin.

g) <u>Methodological differences</u>: Haushild et al. (1966) indicate that the standard USGS P-61 sampler was used to collected integrated, velocity weighted samples at "5 or more" verticals at each station. It is not clear from the information given exactly how concentrations were determined, but personal communication ca. 1993 with a now deceased USGS scientist who served as an outside reviewer on the Hanford project indicated that: a) the concentrations were based on the entire volume sampled, not a sub-sample (as in the 00530 protocol used initially for some NWIS samples); and b) that the sampling effort was extremely high quality, having been conducted by experts in the field of sediment transport. USGS personnel indicate that multiples verticals were sampled for the 1973-2005 NWIS data, but the number of verticals is unclear. Thus, methodological differences are a viable consideration.

h) <u>Sand supply limitation</u>: Sand transport is not supply limited at Vancouver, but Warrendale is only about 4 km below Bonneville Dam. The dam does pass sand, as evidenced by the broad, low angle beaches and islands below Bonneville Dam. However, there appears to have been some erosion downstream of the dam in recent decades, and Bonneville Dam was built on the remains of an ancient landslide that created the rapids at Cascade locks. Thus, it is possible that limitation of sand supply affects the sand load at Warrendale.

i) <u>Secular changes in load</u>: It is hypothetically possible that the load could have decreased over time due to changes in land use, and that this could account for the differences between the loads at Vancouver (1962-1969) and Warrendale (1973-2005). However, given the size of the basin, the decreases documented in Table 1 are unlikely to have occurred due merely to land use changes over a few decades, and land use changes cannot account for the changes in sand load, which is supply limited.

How can the various possibilities be distinguished? Consider first the sand load. The mean and median NWIS sand transports at Warrendale are only 11 to 15% of those measured in 1962-1964.[2] Adding in the Sandy River load (scaled up to the entire surface area of tributaries between Warrendale and Vancouver) increases the ratio of the means to only 16%. Nor can the difference between the sand transports

[2] Note that the maximum sand transport did NOT occur during the December 1964 flood. If the largest sand transport had occurred in December 1964, it would perhaps an unfair comparison to include data from the 1964 flood, because there are no data for the only comparable event in the 1973-2005, the February 1996 flood. Still, the Warrendale data set includes three samples taken during the 1974 and 1997 spring freshets with greater flows at Vancouver than those for the 1964 flood samples used here.

for the two data sets be accounted for by a difference in flows: the mean and median flows are actually higher for the 1973-2005 NWIS data set. The difference between the Warrendale and Vancouver transports, integrated over a 50-year time period (1969-2010) would be 1.7 X 10^8 mtons, corresponding to a bed degradation over the entire reach between Vancouver and Warrendale of ~2m, an amount larger than can be documented, even with the considerable sand mining during the period. We conclude, therefore, that methodological differences may in part be responsible for the differences in sand transports between the data sets. This idea is reinforced by the much greater scatter in the NWIS data set, though the location of the sampling site at Warrendale may reduce the sand load observed. Thus, sand supply is best estimated from the 1962-1964 data, even though this is the older data set.

The mean and median fines load and total loads are also lower at Warrendale than at Vancouver, the differences in the means being a factor of ~1.8 (fines) and ~2.5 (total load), even when the tributaries below Warrendale are considered. Fines transport in the LCR is generally supply limited, e.g., the maximum fines loads observed during the 1974 and 1997 spring freshets were only ~1.5% of the maximum in December 1964, even though the spring flows were actually larger. It is not possible to conclusively distinguish between methodological differences and a reduction in fines supply (likely caused by a combination of the Snake River dams and by changes in land use). The following argument can, however, be made. The mean daily loads for Warrendale plus tributaries and for Vancouver are 8130 and 15,000 mton/day, respectively. Assuming that the available samples are typical of long-term patterns, these loads correspond to annual loads for Warrendale plus tributaries and for Vancouver of 3.0 and 5.5 x 10^6 mtons/yr. This is more than the upper limit of 2 x 10^6 mtons/yr that is likely be trapped in the Snake River and Jon Day Dams, but not greatly more. Thus, a tentative conclusion is that the Warrendale data set can be used to estimate fines load, and that total load should be estimated as a sum of the sand load (from the 1962-1964 Handford project data) plus fines load (from the 1973-2005 NWIS data). This conclusion will be further tested by calculating long-term daily loads from rating curves for each locations. It must be acknowledged, however, that the fines load, the sand load and total loads are all quite uncertain.

Tabulation of flows for Warrendale and Vancouver

Daily USGS flow measurements are provided for The Dalles (station 14105700) and for several tributaries between The Dalles and Vancouver. Daily flows for Bonneville Dam are provided by the US Army Engineers, Northwestern Division (http://www.nwd-wc.usace.army.mil/cgi-bin/dataquery.pl?k=bonneville) on a daily basis since 1960 and on an hourly basis since 1966, but both records have some gaps. Most gaps can be filled with daily flow provided by DART River Environment for 1949 to the present (http://www.cbr.washington.edu/dart/query/river_daily); the few remaining missing observations were interpolated. Vancouver daily flow estimates are provided by USGS for Vancouver (station 14144700) for October 1963 to June 1970, but flows must be routed from points more landward for other periods. For the post 1960 period of interest here, flows were routed from Bonneville Dam using data from the Sandy and Washougal Rivers, as suggested by Orem (1968). However, Washougal River flows are only available up to 1981, after which Sandy River flows were used. In addition, the reported daily Bonneville flows are not believed to be accurate, because they are not consistent (in an average sense) with flows routed from The Dalles, using the tributaries specified by Orem (1968),[3] and the discrepancy is a function of flow. A Bonneville Dam flow correction can be derived by regressing against The Dalles flows the difference between flows routed to Bonneville Dam from The Dalles and those reported for Bonneville Dam. This correction is:

$$\text{Bonncorr}[Q_{TD}] = -0.1569 + 0.04497 \times Q_{TD} \quad (1)$$

Here, Q_{TD} is the daily flow at The Dalles, and Bonncorr is the flow correction, applied to daily flows for Bonneville Dam. Both flows are in units of 10^3 m^3s^{-1}. Determining a correction in this manner allows differences between flows at Bonneville Dam and The Dalles due to reservoir storage to remain in the record. This correction is negative but less than 80 m^3s^{-1} for low flows and close to zero for typical summer flows of 3500 m^3s^{-1}. It reaches +500 m^3s^{-1} for flows of 15,000 m^3s^{-1}.

Daily flows at Vancouver are reported by USGS for the period of sediment transport data collection, 1 July 1962 to 30 September 1969 (Haushild et al., 1966 and station 14144700). Flows for other periods were routed from the corrected Bonneville Dam flows as per Orem (1968).

Definition of rating curves

<u>Sand discharge and total load at Vancouver</u>

The USGS Vancouver 1962-1963 data set is used here for estimation of sand discharge, for reasons described above. Templeton and Jay (2013) derived a sand load rating curve for Vancouver using these data, plus the 1962-1969 total load data. In the present context, the only purpose for the Vancouver total load estimate is to constrain the sand discharge during very high flow periods (Vancouver flows >23,390 m^3/s), so that the sand discharge does not exceed the total load. To quote from Templeton and Jay (2013): "*The resulting rating curves for the Columbia River at Vancouver for total suspended load (L_T), suspended sand load (L_{SS}), and total (bed plus suspended) sand load (L_{TS}) in 10^3 metric tons day^{-1} are (with 95% confidence intervals indicated for the parameters):*

$$\begin{aligned} &L_{T\_CR} = 1.2916 \times 10^{a+b\log(Q_{CR})} \\ &a = -5.886 \pm 0.158 \qquad b = 2.658 \pm 0.043 \end{aligned} \quad (2a)$$

$$\left.\begin{aligned} &L_{SS\_CR} = 0.0001 \\ &L_{SS\_CR} = 0.0001 + a\left(Q_{CR} - 4865\right) \\ &\qquad a = 2.354 \\ &L_{SS\_CR} = a\,Q_{CR}^{0.5} + b\,Q_{CR}^{3.85} \\ &\qquad a = -10.74 \pm 6.96 \quad b = 9.967 \pm 0.109 \times 10^{-12} \\ &L_{SS\_CR} = 0.95\,L_{T\_CR} \end{aligned}\right\} \begin{cases} Q_{CR} < 4865 \\ 4865 \le Q_{CR} < 6000 \\ 6000 \le Q_{CR} < 23{,}390 \\ Q_{CR} \ge 23{,}390 \end{cases} \quad (2b)$$

[3] It is also notable that Orem (1968) did not use Bonneville flows, even though discharge data had been collected at that location since 1949.

$$L_{TS\_CR} = 1.1 \times L_{SS\_CR} \tag{2c}$$

where: Q is river discharge in m^3s^{-1}, the subscript “CR” indicates the Columbia River discharge at Vancouver, and the factor of 1.2916 in (1a) is a “smearing correction” for the effects of data scatter on the power-law rating curve (Duan 1983). The sand transport relation was chosen, after some experimentation, because it fit the data well and had tight confidence limits on the coefficient of $Q_{CR}^{3.85}$ in (1). The ceiling of L_{SS_CR}=0.95L_{T_CR} becomes active only rarely, on 64 days since 1900 and 13 days since 1948. The linear form used between $Q_{CR}^{3.85}$=4865 and 6000m^3s^{-1} is a linear interpolation. The assumption that bedload is 10% of total load, so that L_{TS} is 111% of L_{SS}, derives from Whetten et al. (1969); it was used for the LCR, Willamette and Cowlitz.”

In contrast to the Willamette River, use of a hysteresis correction did not provide any benefit, and, indeed, a hysteresis correction is not expected to be necessary, if transport is transport capacity limited, as is the case for the sand load. The sand load model is shown in Figure 2. The bedload model is not relevant for present purposes, because bedload is not being modeled.

Fines discharge at Warrendale

A hysteresis correction is an important part of the Willamette River load models presented in Appendix II. Some experimentation with the Vancouver total load data suggested that hysteresis was not consistently important. Thus, while the sediment load sometimes increased more rapidly than flow at the beginning of a freshet, freshets (especially in the spring season) are long relative to those in the Willamette, so that the rates of change are relatively smaller. The LCR also has a much larger basin, so the timing of inputs from different sub-basins does not follow a consistent pattern. Thus, for example, the relative timing of flows from the Snake River (with a high load of fines in the 1960s, Haushild et al., 1966) and the Upper Columbia (with less fine sediment) is variable, contributing to inconsistent hysteresis patterns. Seasonality is, however, quite prominent in the fines load, with the loads in the winter being “flashier.” This likely reflects the inputs from Middle Columbia and LCR tributaries with high loads of fines. These tributaries are most active in winter and provide sediment that is less likely to be trapped, because there are fewer dams between the source and Vancouver. Thus, three sediment transport seasons were defined: a) Spring (April to July), b) Fall (August to October), and c) Winter (November to March). All three seasonal load model and weight are formulated as follows:

$$Q_{fines,t} = a\, Q_t^b$$

$$Q_{fines,t} = \text{Fines load (non}-\text{dimensional) at time } t$$

$$Q_t = \text{Discharge (non}-\text{dimensional) at time } t$$

$$t = \text{Time, days}$$

$$a, b = \text{Regression coefficients} \tag{3a}$$

$$wt[t] \sim Log[10, Q_{fines,t}]^n \quad 0 \le n \le 6 \tag{3b}$$

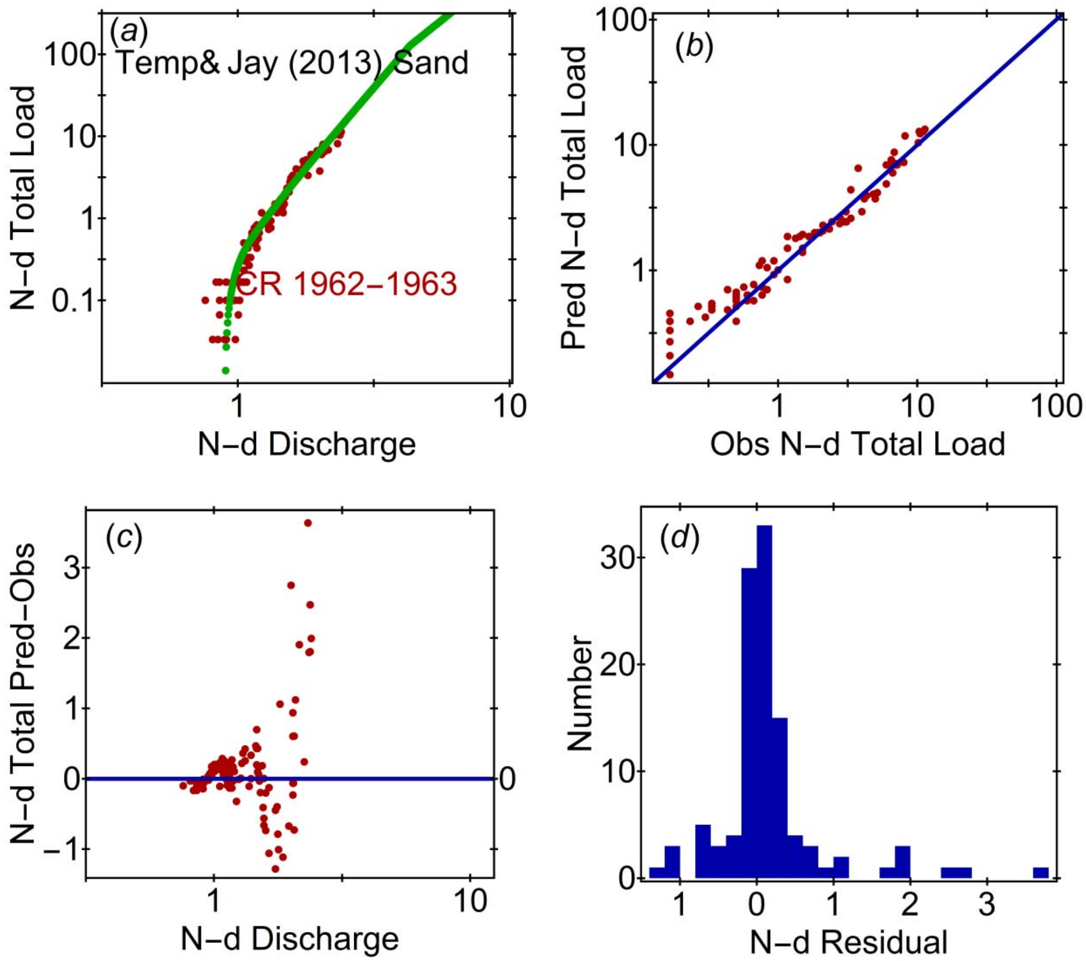

Figure 2: Columbia River at Vancouver sand load regression model results: a) non-dimensional sand load vs. non-dimensional flow, for the data (1963-1063) and the model (green line); b) model predicted vs. observed non-dimensional sand load with a 1:1 line (blue); c) model residuals vs. non-dimensional flow; and d) a histogram of residuals. The model is piecewise and not logarithmic.

Here, fines load Q_{fines} is in mtons/day and discharge Q_t is m^3/s. The weighting scheme is discussed in Appendix II. The idea is to weight high flows somewhat more heavily, so that a log model can be used without resort to a smearing correction. A robust regression is used, to provide more accurate results without discarding any points. This procedure results in models that are as tightly constrained as possible and reproduce the mean of the observed transport relatively well. The Warrendale data set is quite small, however, and the models are not as well constrained as those for the Willamette River, described in Appendix II. The resulting rating curve parameters are shown in Table 1, and Figures 3 to 5 show the fit of the models and the distribution of the residuals. The flows are non-dimensionalized by the mean flow (1960-2015) at Vancouver, while the fines loads are non-dimensionalized by the 1962-1969 median total load at Vancouver. No attempt was made to use the very limited Sandy River data set to predict a Vancouver load – the data were too few to provide a well constrained model. Note that coefficients "a" and "b" are both higher in the winter season than in the other two seasons, reflecting very high winter

Table 2: Fines Load Models for the Columbia River at Warrendale by season, based on 1973-2005 Data

	Parame-ter	a	b	# of points	Adjust-edR^2	n
Model						
Spring		-0.0336±0.04384	2.270±0.170	76	0.904	1.4
Fall		-0.1304 ±0.0552	1.614±0.335	46	0.675	1.8
Winter		0.0867±.0603	3.340±.0.468	74	0.734	3

loads. These are likely due to a combination of greater input from tributaries below John Day Dam and the impact of rain-on-snow events, which produce very large loads. Fines loads during the fall season are small, both because flows are small, and because coefficients "a" and "b" are low. Springfreshet fines loads are generally smaller than those in winter, despite high spring flows in some years.

<u>Lower Willamette Group estimates of total sediment load at Vancouver</u>

The Lower Willamette Group (LWG) provides in Appendix La estimates of total load at Vancouver, even though sand transport is not modeled. The LWG model for total load at Vancouver is based on the 1963 to 1969 data set and is expressed in terms of concentration (C_{CR}) in mg/l:

$$C_{CR} = 0.26 \left(\frac{Q_{CR}}{10^4}\right)^{1.53} \qquad (4a)$$

Here, discharge Q_{CR} is in ft^3/s. The stated R^2 for the concentration model is 0.13; the equivalent R^2 for a load model would likely be somewhat higher. This concentration model is equivalent to the following model for total load Q_{total}:

$$Q_{total} = 0.26 \times 0.0864 \times \left(\frac{35.314}{10^4}\right)^{1.53} \times Q_t^{2.53} \qquad (4b)$$

Here, total load Q_{total} is in mtons/day and discharge Q_t is in m^3/s. Figure 6 shows the behavior of this model. It is evident from the scatter of the data around the model and the large negative residuals that it is difficult to model these data without considering seasonality. The residuals are larger than in Figures 3 to 5 in part because the total load Q_{total} is larger than the fines load Q_{fines}, but the largest issue is the seasonality of the sediment load. The exponent (2.53) in (4b) is intermediate between those for the winter and spring models for the Warrendale data.

We can also compare time series of fines load predicted from the 1973-2005 Warrendale data with fines load predicted from the 1962-1963 Vancouver data and with the LWG total load model based on the 1963-1970 Vancouver data. (Note that seasonal plots similar to Figures 3 to 5 were made for the fines load predicted from the 1962-1963 Vancouver data; they are not shown here, because these models were not selected as optimal.) Two kinds of simple comparisons can be made: a) the annual loads predicted by the three models (Figure 7); and b) the daily loads predicted by the models (Figures 8 and 9).

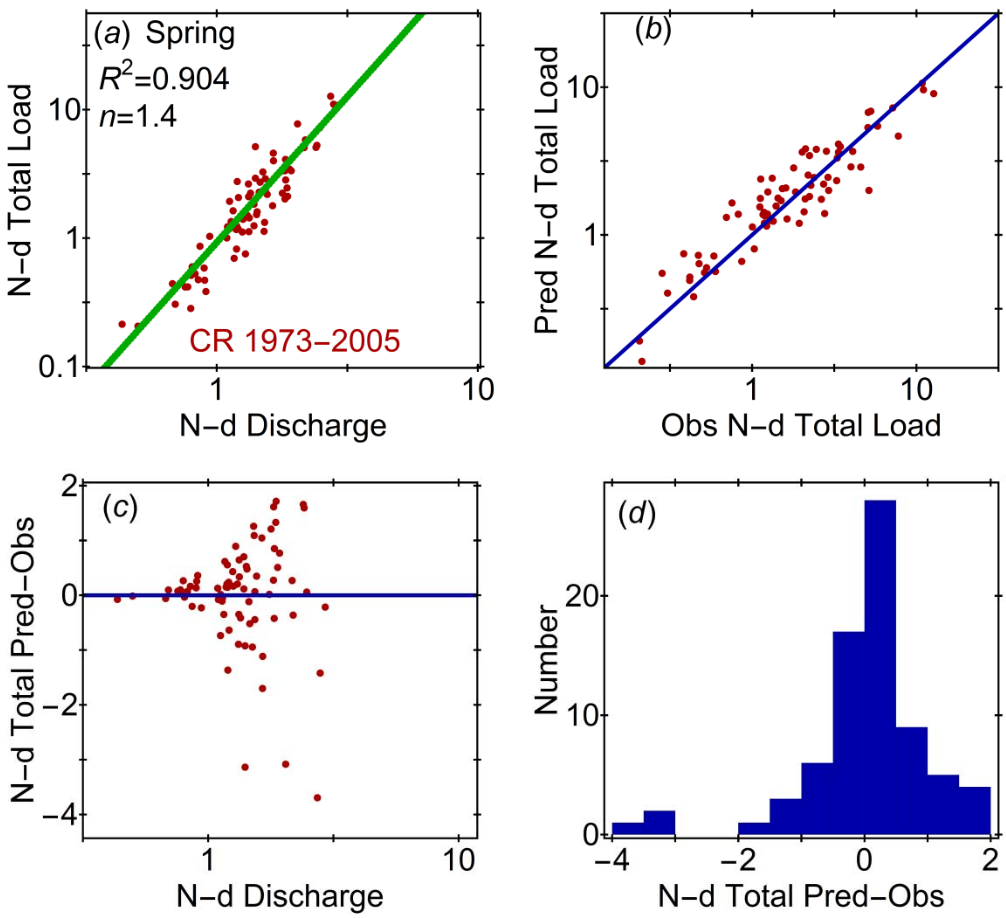

Figure 3: Columbia River at Warrendale fines load regression model results for the spring season: a) non-dimensional fines load vs. non-dimensional flow, for the data (1973-2005) and the model (green line); b) model predicted vs. observed non-dimensional fines load with a 1:1 line (blue); c) model residuals vs. non-dimensional flow; and d) a histogram of residuals. The loads are larger than in fall, but smaller than in winter; the model is well-constrained, and the residuals are relatively symmetrical.

The daily loads are useful in that they reveal the seasonality of the differences in predicted flows. The annual loads shown in 1996-1997 emphasize that predicted LWG Vancouver total loads are much smaller than the fines loads predicted by either of the other in years with high winter flows, like 1996 and 1997. They are also lower in high flow years like 1972, 1974, 1981 and 1982, but not in 2011. The Vancouver fines model based on the 1962 to 1963 data predict higher loads than the model based on the Warrendale (1973-2005) data, as already noted, except for years like 1996 and 1997 with winter floods, where they are comparable. For most low-to-average flow years since 1987, the LWG Vancouver total load model predicts higher loads than the seasonal fines load models based on the Warrendale data. Given that the LWG model predicts total load rather than fines load, this is not surprising. However, this does emphasize that the suspended fines load at Vancouver is probably being overestimated in Portland Harbor modeling, except during years with winter floods, when it is drastically under-estimated.

Figure 8 emphasizes that the fines load during the spring freshet and the fall predicted from the Warrendale data is much lower than estimated by either of the other two models. On the other hand, the two fines load models agree fairly closely for winter high flows, while the LWG Vancouver model predicts a much lower load. This is shown more clearly in Figure 9, which focuses on the generally high-flow period from fall 1995 to 1998. Unfortunately, there are no observations during the floods in February 1996 and January 1997.

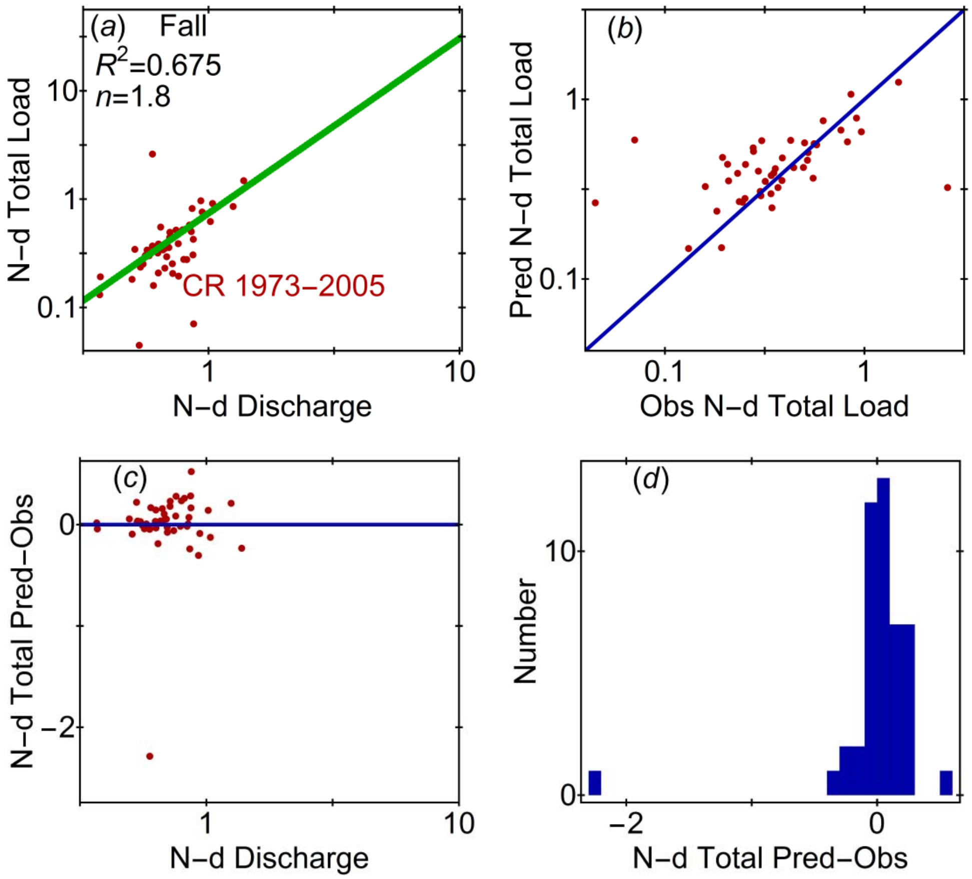

Figure 4: Columbia River at Warrendale fines load regression model results for the fall season: a) non-dimensional fines load vs. non-dimensional flow, for the data (1973-2005) and the model (green line); b) model predicted vs. observed non-dimensional fines load with a 1:1 line (blue); c) model residuals vs. non-dimensional flow; and d) a histogram of residuals. The data are rather scattered and the R^2 is relatively low, but the residuals are small, because the load is small.

Discussion and conclusions:

It is clear from the divergence of the three models for the load at Vancouver that the uncertainty in this load is quite large. Several recommendations stem from this uncertainty:

a) <u>Sensitivity analyses (sediment transport)</u>: The uncertainty in sediment transport modeling due to this poorly determined boundary condition need careful evaluation, particularly with respect to the behavior of the model during major winter storms, when fine sediment inputs are high.

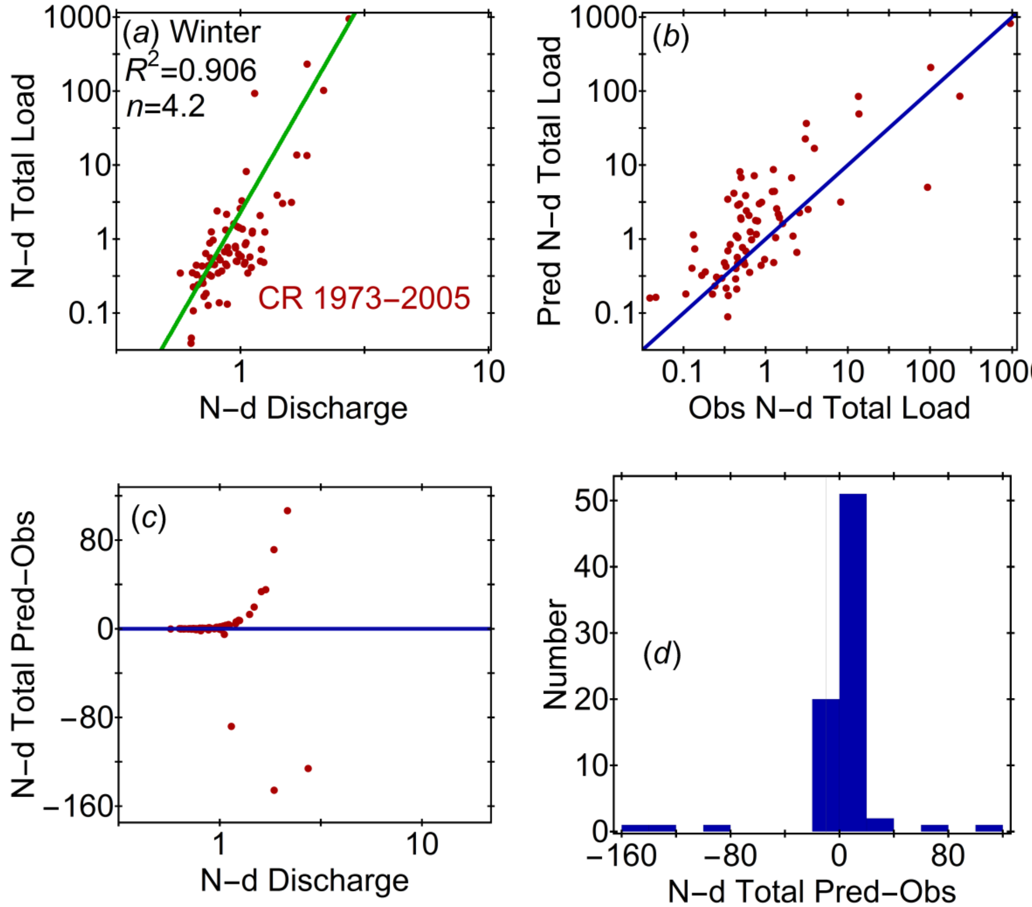

Figure 5: Columbia River at Warrendale fines load regression model results for the winter season: a) non-dimensional fines load vs. non-dimensional flow, for the data (1973-2005) and the model (green line); b) model predicted vs. observed non-dimensional fines load with a 1:1 line (blue); c) model residuals vs. non-dimensional flow; and d) a histogram of residuals. Note the much higher winter loads and the large scatter of the data, resulting in larger residuals than in spring and fall. The largest errors are for days with very high loads, in which case the model under-predicts the actual load. Residuals are, however, smaller than for the LWG Vancouver total load model.

b) <u>Sensitivity analyses (contaminant transport)</u>: The impact of uncertainty in contaminant inputs on contaminant transport modeling should be evaluated, especially during winter high-flows, when fine sediment inputs are large.
c) <u>Data collection</u>: Modern observations of sediment concentration and load at Vancouver are urgently needed for multiple purposes. USGS has recently installed a side-looking ADCP near Portland Airport. If these data are properly calibrated, they could be used to provide improved estimates of fines load at the upstream model boundary, near Vancouver.

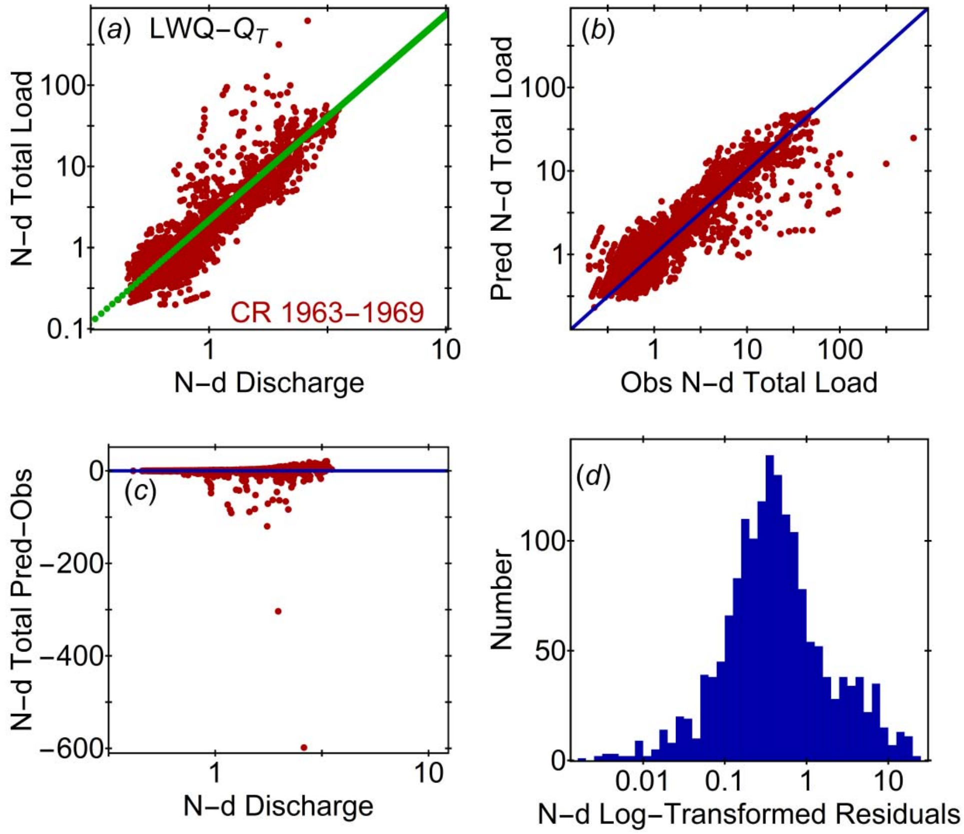

Figure 6: LWG regression model of Columbia River total load at Vancouver (all seasons combined): a) non-dimensional total load vs. non-dimensional flow, for the data (1963-1969) and the model (green line); b) model predicted vs. observed non-dimensional total load with a 1:1 line (blue); c) model residuals vs. non-dimensional flow; and d) a histogram of residuals. Note the large scatter of the data and the large negative residuals that result from modeling all seasons together. The large residuals occur primarily for winter days with very large sediment loads.

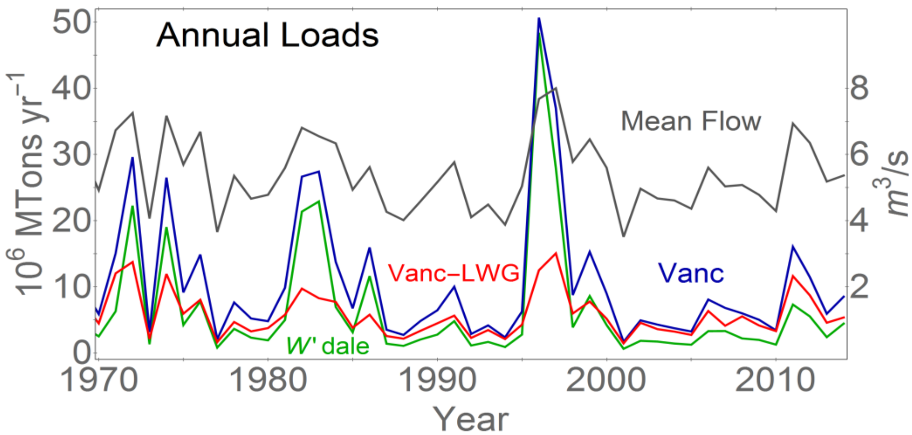

Figure 7: Routed mean annual flows at Vancouver (gray) and annual loads for 1970 to 2015 predicted from: the Warrendale (1973 to 2005) seasonal fines load models shown in Figures 3 to 5 (green); the Vancouver seasonal fines load models based on 1962 to 1963 data (blue), and the LWG Vancouver total load model shown in Figure 6 and based on the 1963 to 1969 data set (red). Note that no allowance has been made in any of the models for the removal of Marmot Dam on the Sandy River in 2007. This resulted in a pulse of sediment, some of which was presumably transported to Vancouver. Annual flows and loads are based on the water year (October to September).

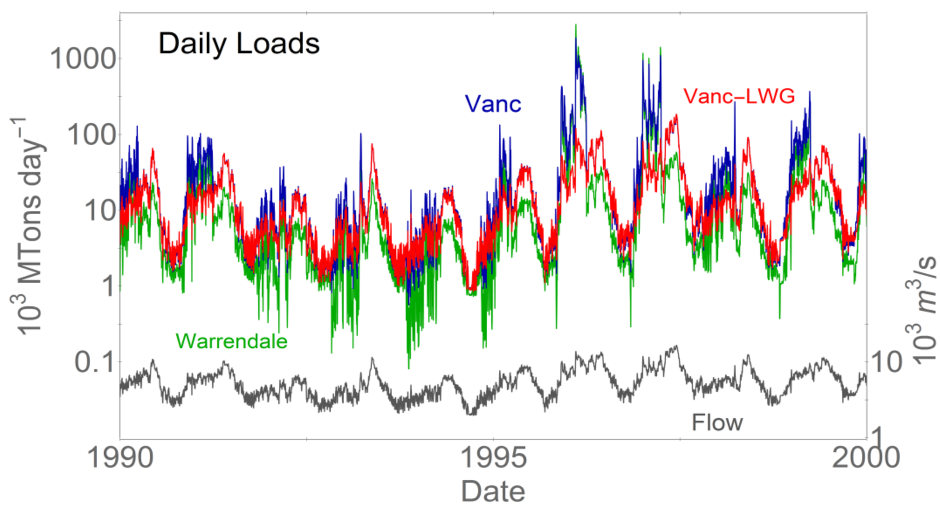

Figure 8: Routed daily flows at Vancouver (gray) and daily loads for 1990 to 2000. The colors and models are as in Figure 7.

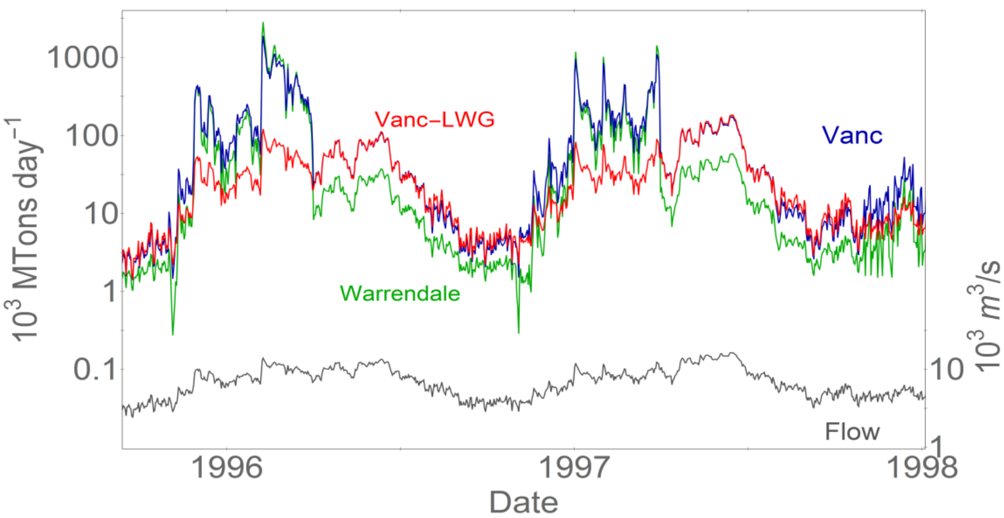

Figure 9: Routed daily flows at Vancouver (gray) and daily loads for October 1995 to the end of 1997. The colors and models are as in Figure 7.

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